REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
05-02-2016	Final Report	17-Aug-2012 - 16-Nov-2015

4. TITLE AND SUBTITLE
Final Report: Innovative Facet Passivation for High-Brightness Laser Diodes

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W911NF-12-C-0071

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS
Dr. Jonah Jacob, Dr. Aland Chin

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Science Research Laboratory, Inc.
15 Ward St

Somerville, MA 02143 -4241

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
62329-EL-DRP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

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15. SUBJECT TERMS
high-power laser diodes, catastrophic optical damage, high energy lasers

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jonah Jacob
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					617-547-1122

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

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Number of Presentations: 0.00

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Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

<u>Received</u> <u>Book</u>

TOTAL:

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TOTAL:

Patents Submitted

Patents Awarded

Awards

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NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

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REPORT DOCUMENTATION PAGE

Approve
O[Form] MB No. 0704-0[d]

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1. REPORT DATE *(DD-MM-YYYY)*
11-16-2015

2. REPORT TYPE
FINAL

3. DATES COVERED *(From - To)*
08-17-2012 TO 11-16-2015

4. TITLE AND SUBTITLE
Innovative Facet Passivation for High-Brightness Laser Diodes

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Science Research Laboratory Inc
15 Ward St.
Somerville, MA 02143

8. PERFORMING ORGANIZATION REPORT NUMBER
SRL401 11-16-15

9. SPONSORINGIMONITORING AGENCY NAME(S) AND ADDRESS(ES)
US ARMY RDECOM ACQ CTR - W911NF
P.O. Box 12211
Research Triangle Park, NC 27709-2211

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Unclassifed	Unclassifed	Unclassified	Unclassified	27	Dr. Jonah Jacob
					19b. TELEPHONE NUMBER *(Include area code)* 617-547-1122 x139

Standard Form 298 (Rev. 8/98)

Prescribed by ANSI Std. Z39.111 Adobe Professional 7.0

SRL401 11-16-15

INNOVATIVE FACET PASSIVATION FOR HIGH-BRIGHTNESS LASER DIODES

INTERIM REPORT

August 17, 2012 TO November 16, 2015

Prepared for

U.S. Army Research Office

PO Box 1211

Research Triangle Park, NC 27709-2211

Prepared by

Science Research Laboratory Inc

15 Ward Street

Somerville, MA 02143

Table of Contents

1: Introduction

The objective of this effort is to increase the power of low fill-factor (~20%) laser diode (LD) bars from the present state-of-the-art (SOA) of 60-70 W/bar to 300 W/bar – a five-fold increase. To achieve this dramatic 5X increase in the power/bar SRL will attempt to increase the power at which SOA LDs fail, namely, increase the threshold for catastrophic optical damage (COD) of the LD mirrors by improving the passivation of the facets. The SOA facet passivation is the E2 passivation that was invented by IBM in the early 1990s. [(1)] As presented below, while E2 passivation is perfectly acceptable for SOA bars operating at 60-70 W, it is not capable of withstanding the 300 W/bar desired for our military high energy lasers (HELs).

COD of the front facet (laser mirror) is the main failure mechanism that constrains scaling LD power to 300 W per bar. [1] COD is due to absorption at the facets as a result of dangling bonds produced during the facet formation process (cleaving) or from contamination from the ambient.

Recent advances in thermal management, bonding and long gain-length LD technologies developed by Science Research Laboratory (SRL) under DARPA's EXCELS program reduce thermal roll-over and should permit LD power scaling to the 300W level. Unfortunately, existing facet passivation has not kept pace with packaging and LD technologies and presently limits the SOA power and brightness. In this effort, SRL is developing a novel facet passivation technology based on molecular beam epitaxial (MBE) growth of $Al_XGa_{1-X}As$ (where x represents the mole fraction) at relatively low temperatures compatible with existing LD semiconductor fabrication.[2] LD wafers are cleaved in ultra-high vacuum (UHV), < 10^{-9} Torr to form the LD facets which are then passivated in-situ using a thin film of high band gap, lattice-matched, single crystal $Al_XGa_{1-X}As$ that is transparent to the laser emission, thus forming a protective optical window. Unlike E2 passivation, this lattice-matched, single-crystal thin film will eliminate optically-absorbing threading-dislocations, grain boundaries, and dangling bonds near the front facet. In addition it will increase the band gap at the facet thereby reducing laser photon absorption and increasing the COD limit. In addition this window coating will protect the facet from the ambient. (See Figure 1.1)

The UHV processing will prevent oxidation of the front facet, the leading contaminant from the ambient. By keeping the MBE growth temperatures between 400 and 500 ^{O}C, sufficiently high quality crystalline AlGaAs material should be achieved while ensuring that the electrical conductivity of the metal contacts is not degraded. That is, there exists a thermal "sweet spot" (discussed in detail below) compatible with high quality AlGaAs growth and stability of the Ohmic contacts. (See Figure 1.2.) Performing passivation in this temperature range is most

[1] LD brightness constrains LD bars used for fiber laser pumping to 20% fill-factor. For solid-state slab lasers >50% LD bars can be used and they should scale to well over a 1,000 W/bar.

[2] Although this project focuses on 980 nm, 20% FF LDs, AlGaAs passivation applies equally well to most other GaAs-based LDs ranging from the visible to the near infrared regardless of fill factor, utilizing the same UHV equipment, albeit with suitably adjusted Al mole fraction and growth recipes. Specifically, MBE-AlGaAs passivation can apply to slab pumped lasers (e.g. 808 nm), fiber lasers (97x nm), and DPALS (79x nm). In fact, the same technique and equipment can be used to apply coatings to InP- or GaSb-based LDs as well.

important as it is consistent with present LD fabrication thereby eliminating the need to develop entirely new fabrication procedures or fixturing – an extremely expensive endeavor.

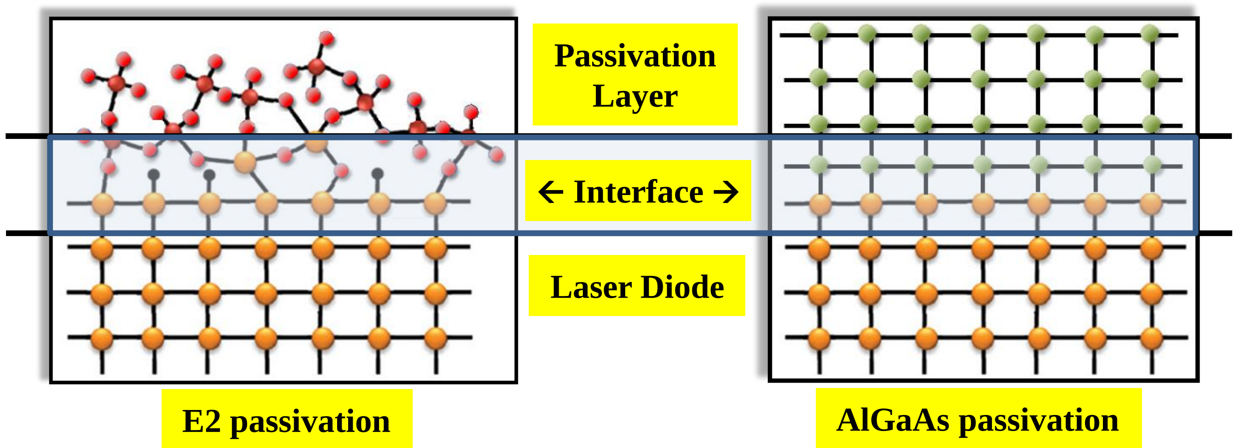


Figure 1.1: (a) Amorphous passivation, e.g. E2, and (b) lattice-matched passivation, e.g. AlGaAs

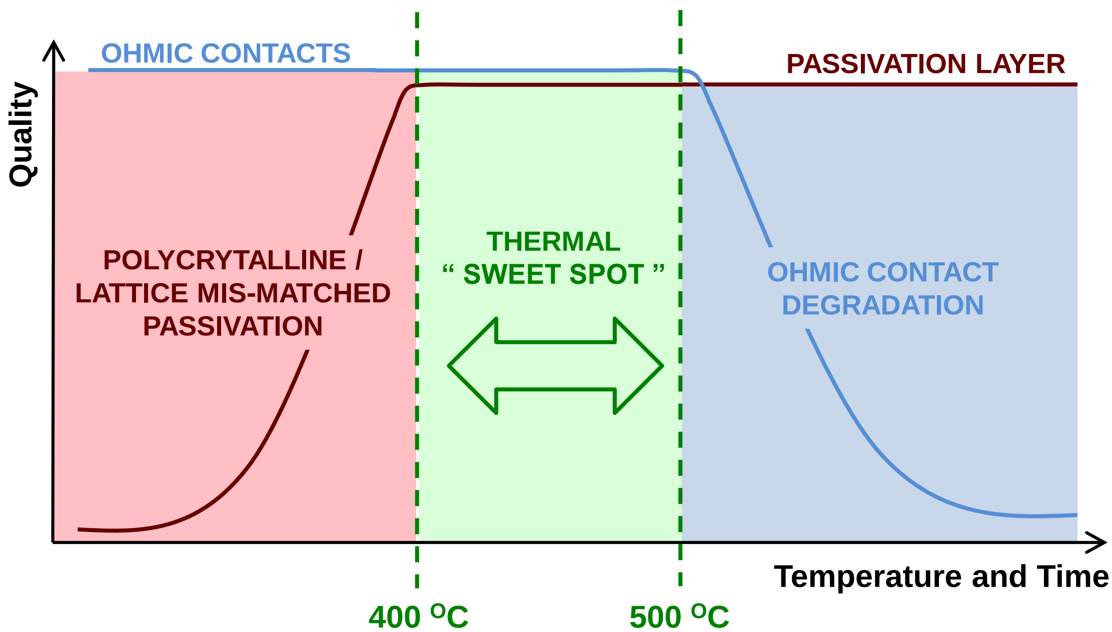


Figure 1.2: Thermal "sweet-spot"

1.1: Military / DARPA Relevance

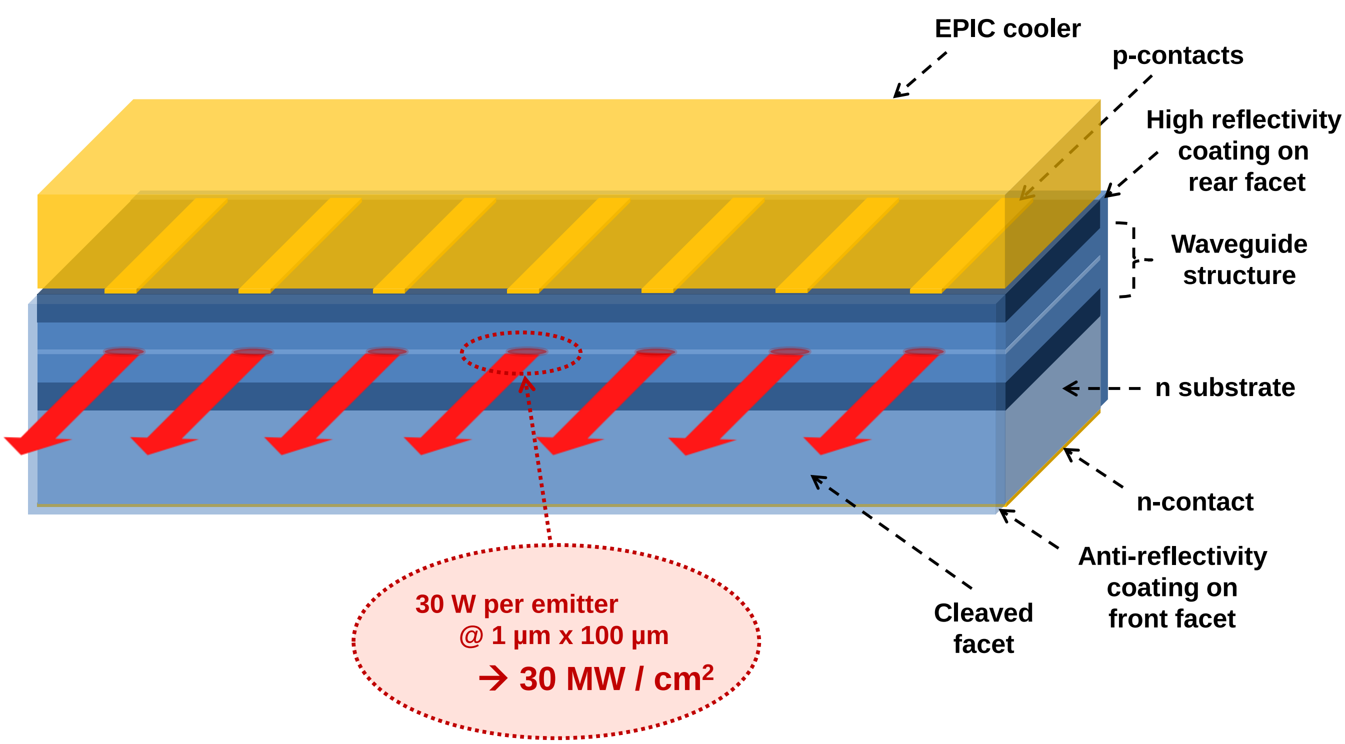
Laser diodes arrays (LDAs) are used to pump, and hence a critical component of several DARPA/DOD HEL efforts including:

- Solid-state slab lasers being developed by HELLADS,
- Fiber lasers developed under EXCALIBUR and,
- More recently diode pumped alkali lasers (DPALS).

For these HELs high power and brightness LDs are key parameters for decreasing the size, weight and cost of LDAs while simultaneously increasing their performance. Because weight and cost per bar are very weak functions of power, increasing power/bar by a factor of five will increase the power-to-weight (P/W) ratio by almost 5X and decrease the weight of LD pump modules, in these systems, by almost a factor of five. An additional important benefit of increased bar power, the cost for these LD bars will decrease by approximately 5X.

1.2: LD Failure by Catastrophic Optical Damage

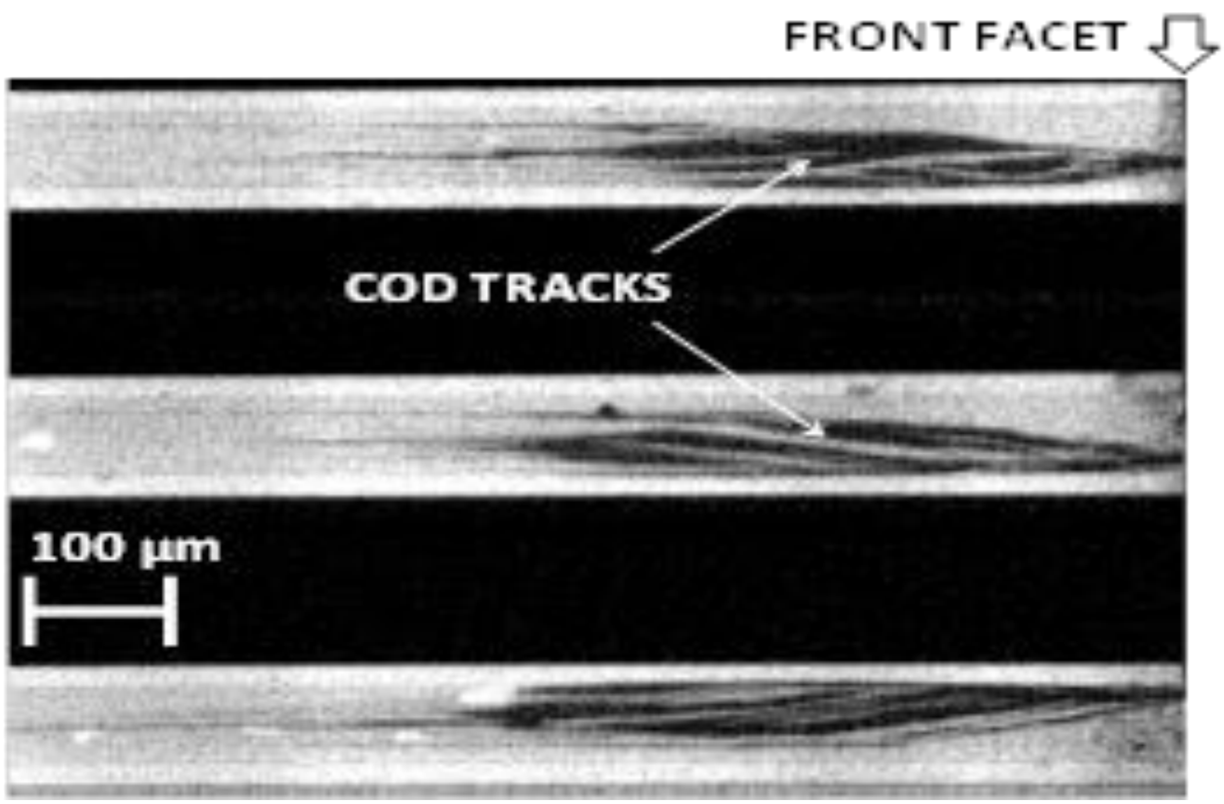
The LD gain, waveguide, and cladding layers are formed by epitaxial growth on a substrate, in this case (100) GaAs. After metallization, the optical cavity is formed by cleaving the wafer along the (110) plane which results in nearly atomically smooth facets. High reflectivity (HR) and anti-reflection (AR) coatings are deposited after cleaving. Edge-emitting laser diodes emit very high optical powers from small emission areas, as shown in Figure 1.3. Therefore, the optical intensity at the front facet is extremely high, on the order of several tens of MW/cm^2. COD is caused by absorption of the laser photons by a variety of processes including dangling bonds, threading dislocations, oxidation, and amorphous or low bandgap passivation at the front facet. This absorption leads to heating of the semiconductor which shrinks the LD bandgap, which results in increased absorption and a further shrinkage of the bandgap. Such a thermal runaway process ultimately melts the semiconductor. Images of COD taken by SRL are shown in Figure 1.4(a).[3]



[3] For more details including a movie of COD propagation, visit http://www.srl.com/COD_propagation.html

Figure 1.3: Edge-emitting laser diode

As stated above, COD at the front facet is the primary mode of failure in high power, high brightness GaAs-based LDs. In addition to E2 passivation, there exist other (less common) passivation techniques designed layers to reduce the optical absorption on the cleaved facet. [(1), (2), (3), (4)] Although most of these passivation layers offer a level of protection against COD adequate for SOA LDs operating at ~ 60 W/bar, none offer sufficient protection to operate these LDs at the 300 W/bar power levels required by HELs. On SOA thermal management, SOA passivated LDs experience thermal rollover at 100 W/bar well before failure via COD. However, these diodes, when mounted on extremely low thermal resistance microchannel coolers such as SRL's EPICs, operate at significantly reduced junction temperatures and therefore avoid thermal rollover at >350 W/bar. These diodes on EPICs then fail by COD before attaining the power levels required by DoD HEL systems, as shown in Figure 1.4(b) and Figure 1.5. This is not surprising when details of each SOA passivation technique are examined in detail. Each is either lattice or thermal expansion mismatched (both of which lead to passivation layers with significant defect densities and/or polycrystalline material) or requires high growth temperatures incompatible with current laser diode processing. These limitations are reviewed in detail below. Clearly facet passivation is required that is lattice and thermal expansion matched to GaAs based LDs and which can be grown at temperatures compatible with the pre-existing Ohmic contacts. The GaAs-based material system is shown in Figure 1.6 depicting the excellent lattice match of AlGaAs and the poor lattice match of silicon.



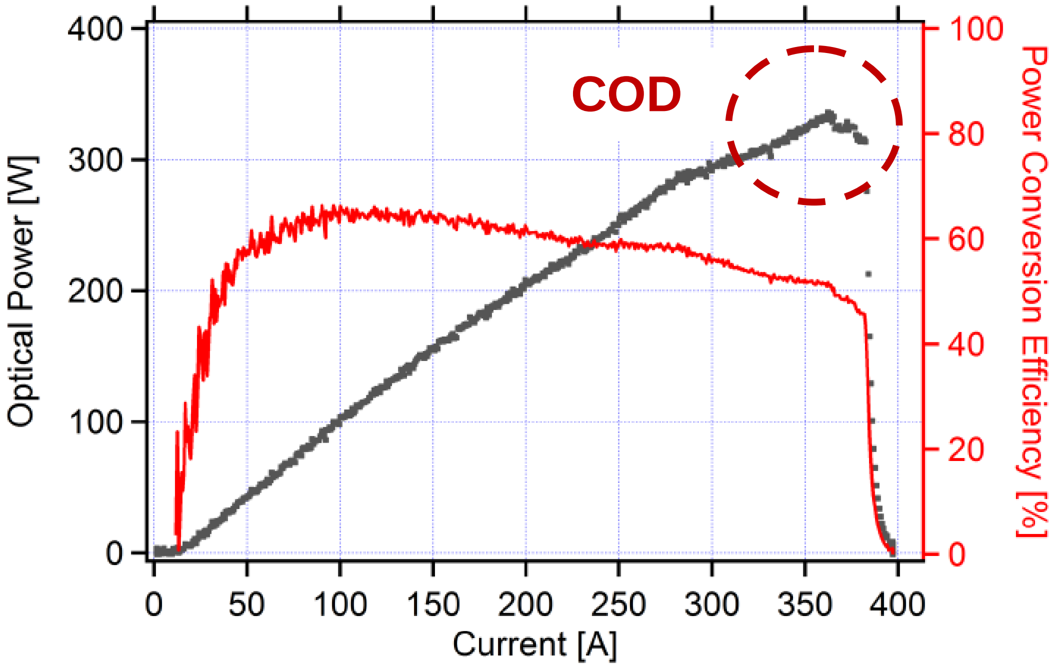


Figure 1.4: (a) COD emanating from the front facets of 3 LD stripes, and (b) COD in an E2 passivated LD

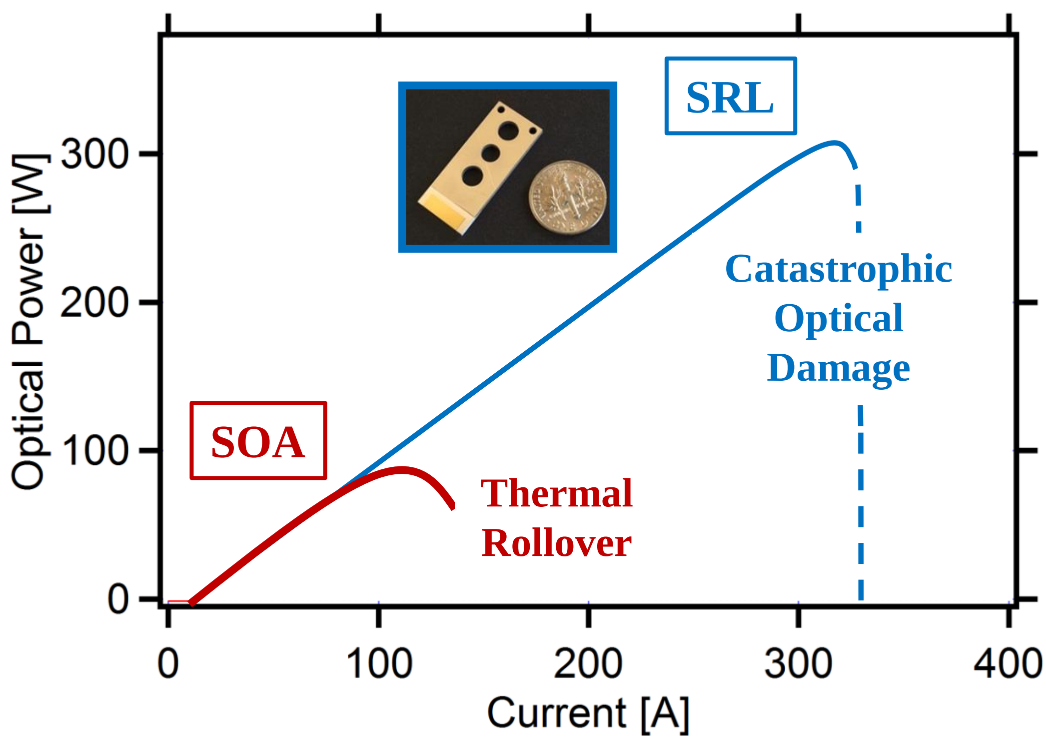


Figure 1.5: Performance of LD mounted on SOA thermal management versus SRL EPIC (shown in inset)

1.3: Ideal Passivation

The ideal facet passivation possesses many characteristics each of which are critical if the passivation layer is to prevent COD at very high power levels. These characteristics are discussed in detail below and listed in Table1.1.

(1) **Prevents Oxidation**: The passivation layer must prevent oxidation of the facet since oxygen is known to introduce significant density of surface states into the bandgap. Some passivation techniques attempt to remove the oxide just prior to deposition of a passivation layer and/or the optical coatings but this approach has consistently been shown to be inferior to passivation techniques where the passivation layer is applied in situ after cleaving without ever breaking ultra-high vacuum.

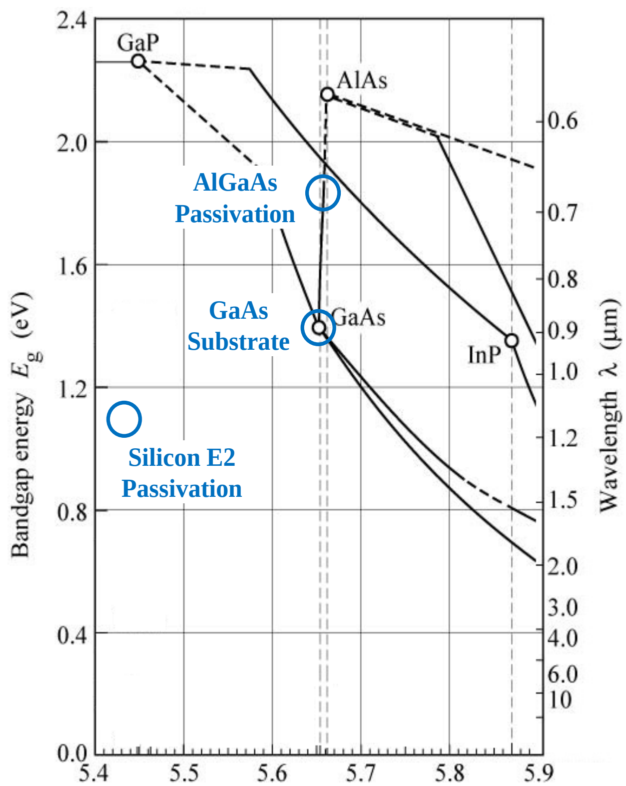


Figure 1.6: The GaAs-based material system

(2) **Lattice Matched**: The passivation layer must be lattice matched in order to satisfy every dangling bond that results from the abrupt termination of the laser diode crystal structure upon cleaving along the (110) crystal plane.

(3) **Single Crystal**: The passivation layer must be single crystal without threading dislocations since extended defects and grain boundaries will strongly absorb laser photons. This condition is met by use of a lattice matched passivation layer which leads to single crystal growth. Lattice mismatches lead to misfit dislocations at the interface and stresses that result in threading dislocations and polycrystalline or amorphous material.

(4) **Thermal Expansion Matched**: The passivation layer must be a good thermal expansion match to the laser diode. Since growth or deposition of the passivation layer is performed at elevated temperature, as the laser diode cools back to room temperature, stresses develop that can lead to threading dislocations and polycrystalline or amorphous material.

(5) **High Bandgap**: The passivation layer must have a higher bandgap than the photon energy or it will strongly absorb the laser radiation. Since no growth is perfect, a certain number of shallow defect states are expected just above the valence band and just below the conduction band of the passivation material. Thus the bandgap of the passivation should be large enough to ensure that transitions between these states are larger than the laser photon energy.

(6) **No Diffusion**: The constituent atoms of the passivation layer and LD should not inter-diffuse. Diffusion of the atoms will lead to thermal instability and the generation of defect states that will absorb the laser.

(7) **Refractive Index Matched**: Ideally, the passivation layer has the same refractive index as the LD so that existing HR and AR coating deposition recipes can be used without alteration. Significant refractive index mismatches require redesign of the optical coatings.

(8) **Compatible with LD Processing**: The passivation process should also be compatible with existing laser diode semiconductor processing. This, of course, impacts critically the commercial viability, availability and scalability of the technology.

Ideal Passivation	State-of-the-Art			SRL
	E2	ZnSe	InGaAsP	AlGaAs
Prevents Oxidation	✓	✓	✓	✓
Lattice Matched	✗ (4%)	✗ (0.27%)	✓	✓
Single Crystal	✗	✗	✓	✓
Thermal Expansion Matched	✗ (220%)	✗ (33%)	✓	✓
High Bandgap	✗ (1.1 eV)	✓	✓	✓
No Diffusion	✓	✗ (Zn)	✓	✓
Refractive Index Matched	✓	✗ (2.5 vs. 3.3)	✓	✓
Compatible with LD Processing	✓	✓	✗ (High T Growth)	✓

Table 1: Various passivations compared with the ideal

1.4: AlGaAs Passivation

As shown in Table1, AlGaAs possesses all these attributes with respect to GaAs-based laser diodes. Specifically:

(1) **Prevents Oxidation**: Cleaving the diodes in UHV and then transferring them to the MBE growth chamber without breaking vacuum will prevent oxide formation on the facet prior to passivation. The AlGaAs layer itself will prevent oxide formation after passivation.

(2) **Lattice Matched**: Since AlAs is an excellent lattice match (0.1%) to GaAs (see Figure III.6), any ternary made from them, i.e. $Al_XGa_{1-X}As$, will also be an excellent lattice match. This will ensure dangling bonds at the cleaved facet are satisfied.

(3) **Single Crystal:** The excellent lattice match will also ensure that the passivation layer will be single crystal without threading dislocations and grain boundaries. The low temperature growth will lead to a certain number of point defects (<1e18/cm^3) [15] but, as discussed below, these will not be problematic.

(4) **Thermal Expansion Matched:** Since 980 nm laser diodes are made from GaAs and AlGaAs, AlGaAs passivation is an excellent thermal expansion match as well. The CTE mismatch will be < 4% over the range of Al mole fractions anticipated in this effort. The AlGaAs layer is also well CTE matched to the ~ 7 nm thick InGaAs QW layer.

(5) **High Bandgap:** The bandgap of $Al_XGa_{1-X}As$ depends on the Al mole fraction, x. In 980 nm laser diodes, the waveguide layers are typically comprised of $Al_XGa_{1-X}As$ with x ~ 0.22 which represents a bandgap energy about 30% larger than the laser photon energy.

(6) **No Diffusion:** AlGaAs is used extensively in GaAs-based laser diodes and is known to be stable against diffusion. LDs containing AlGaAs layers have demonstrated lifetimes measured in tens of thousands of hours.

(7) **Refractive Index Matched:** Although the refractive index depends on Al mole fraction, the AlGaAs passivation layer will be matched to the waveguide layers to within 4% and will also be much less than ¼ wavelength thick. Optical coatings will be applied over the passivation. Thus, the passivation layer will not require redesign of the optical coatings.

(8) **Compatible with LD Processing:** High quality, high mobility AlGaAs can be grown on the (110) GaAs facet at low to moderate temperatures, 400 to 500 ^{O}C. [12], [16] Since the passivation layer is only ~ 10 nm thick, growth times will be short, about 5 minutes. These growth temperatures and durations are compatible with state-of-the-art LD semiconductor processing including the Ohmic contacts. [9], [10], [11]

1.5: Summary

As stated above, the goal of this program is to increase the optical power at which a 980nm, InGaAs/AlGaAs/GaAs laser diode fails by catastrophic optical damage (COD) by growing a transparent $Al_xGa_{(1-x)}As$ passivation-layer, latticed matched, epitaxial layer on the facets using MBE. COD occurs where absorption of the laser light results in a temperature that exceeds the melting temperature of the material. Typically this occurs at the front facet within the waveguide layers, the spatial intersection of the highest optical intensity and the highest optical absorption. While the front and rear facets have similar absorption, the optical power density is greatest at the front facet. The rear facet is optically coated so that the reflectivity exceeds 95% and the front facet is optically coated so that the reflectivity is small, typically ~5% so that most of the laser power exits the cavity at the front facet.

The novel aspects of this program are:

1. Forming the facets by cleaving the wafer in ultra-high vacuum ($<10^{-9}$ Torr.) to minimize contamination.
2. Forming the facets and subsequently growing the epitaxial passivation layers on metalized wafers, thus causing minimal changes to standard laser diode fabrication.
3. Growing the epitaxial layer by molecular beam epitaxy (MBE) at a temperature of ~500°C which is expected not to affect laser diode performance yet produce defect free epitaxial material.

2: Background Information

Ohmic contacts for LDs are formed by alloying (n-contact) or sintering (p-contact) at ~420°C for ~20s in forming gas. There is a concern that MBE growth @ ~500°C for 1hr in ultra-high vacuum may degraded the ohmic contacts.

Molecular beam epitaxy (MBE) growth of GaAs/GaAlAs epitaxial layers is normally performed in the temperature range of 600°C to 700°C. The high substrate temperature results in high surface mobility, thus resulting in high material quality.

The GaAs substrate for laser diodes in nominally oriented along the <100> direction so that the (110) cleavage planes are perpendicular to the (100) surface. The laser diode mirrors are formed by cleaving the wafer along the (110) directions. MBE growth conditions depend on the substrate surface. See Fig. 2.1 and 2.2.

The orientation of the GaAs substrate is normally a few degrees misaligned from the <100> direction to expose growth initiation sites. The cleaved facets of the laser diode are exactly the (110) surfaces, thus there are minimal growth initiation sites.

Modern laser diode structures are separate confinement, double heterostructures. The optical field is confined to the quantum well and waveguide layers. See Fig. BI.3A.

Absorption at the facet is significantly increased relative to the rest of the optical cavity due to:

1. Mechanical damage from the cleaving process.
2. Chemical reaction of the semiconductor (GaAs, $In_xGa_{(1-x)}As$, $Al_xGa_{(1-x)}As$) with the ambient, e.g. O_2.
3. Adsorption of contaminants in the ambient, e.g. H_20, CO_2, hydrocarbons.

The growth of a transparent window-layer, latticed matched, epitaxial layer on the facets of the LD reduces absorption at the facets and thus increases the power at which the LD fails by COD. See Fig. 2.3B.

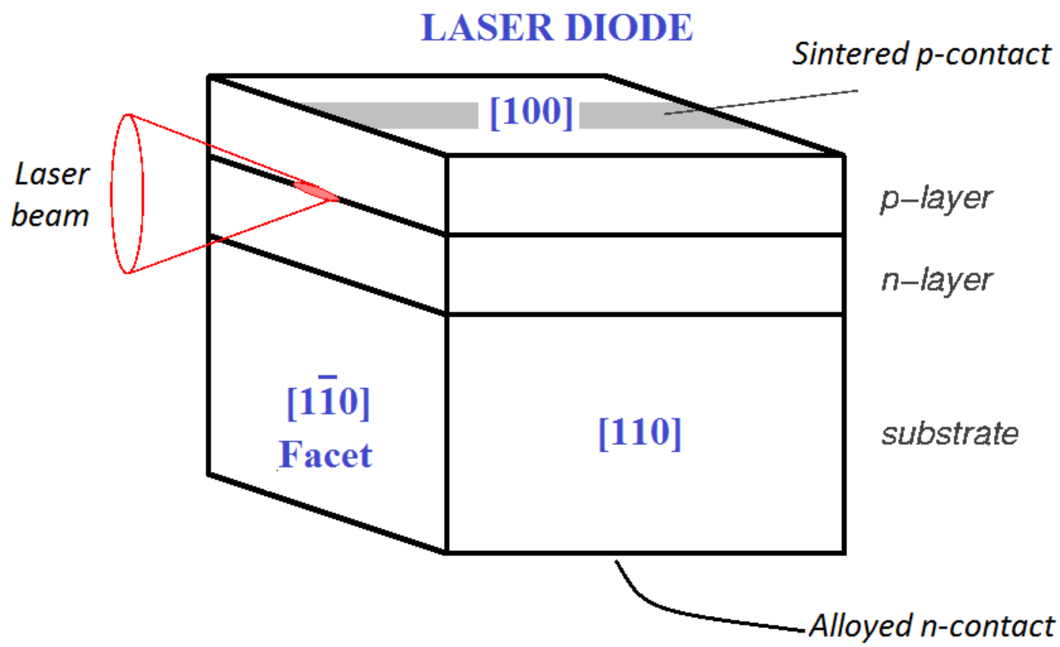


Figure 2.1 General description of a laser diode.

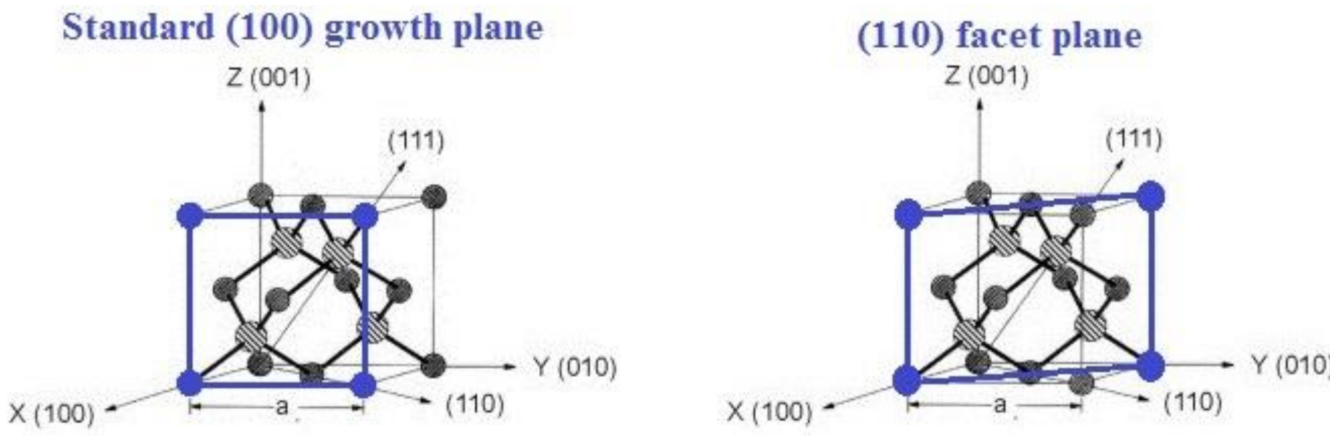


Figure 2.2 Comparison of (100) and (110) crystal planes in GaAs.

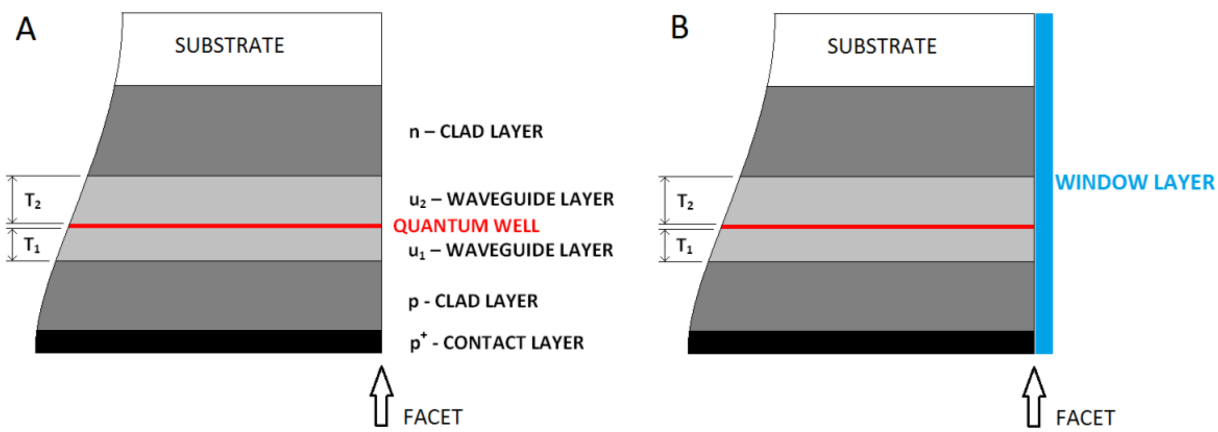


Figure 2.3 A) Side view of single quantum-well, separate confinement, double heterostructure laser diode. B) Same as A with the addition of a transparent window layer epitaxially grown on the facet.

3: The Following Tasks of Epitaxial Passivation Program have been completed

1. Procure laser diode (LD) cells [sections of laser diode wafers processed to the point of facet formation].
2. Determine optical power at which LD-bar, with standard high reflectivity/low reflectivity optical coatings (OCs), fails by catastrophic optical damage (COD).
3. Demonstrate that ohmic contacts are unaffected by exposure to intended MBE growth conditions, i.e. 500°C, 1hr, ultra-high vacuum (~10^{-9} Torr) [UHV].
4. Demonstrate cleaving of cells in UHV.
5. Determine MBE growth conditions at 500°C for defect free $Al_xGa_{(1-x)}As$ (x~0.2) [epitaxial passivation layer (EPL)] on <100> oriented GaAs substrates. Demonstrate EPL.

6. Determine MBE growth conditions at 500°C for EPL on <110> oriented GaAs substrates. Demonstrate EPL.
7. Determine MBE growth conditions at 500°C for EPL on single (110) facet, formed in air, of LD-bar. Demonstrate EPL.

4: Program Status

1. Procure laser diode (LD) cells [sections of laser diode wafers processed to the point of facet formation].
   Status: Complete

- A high efficiency laser diode structure was designed in collaboration with Prof. Lin Zhu of Clemson University.
- Eleven 3"-diameter LD-wafers were procured from IQE (www.iqep.com).
- Photomasks (Fig. 4.1) were designed for 4mm cavity length, nineteen 100µm-wide emitters, 500µm pitch LDs in collaboration with Cutting Edge Optronics [CEO} (www.northropgrumman.com).
- CEO fabricated 12mm wide cells (Fig. 1.2A), each containing multiple 4mm cavity length LD-bars, from 2 of the LD-wafers.
- CEO pre-scribed (Fig. 4.2B) the cells for facet formation.

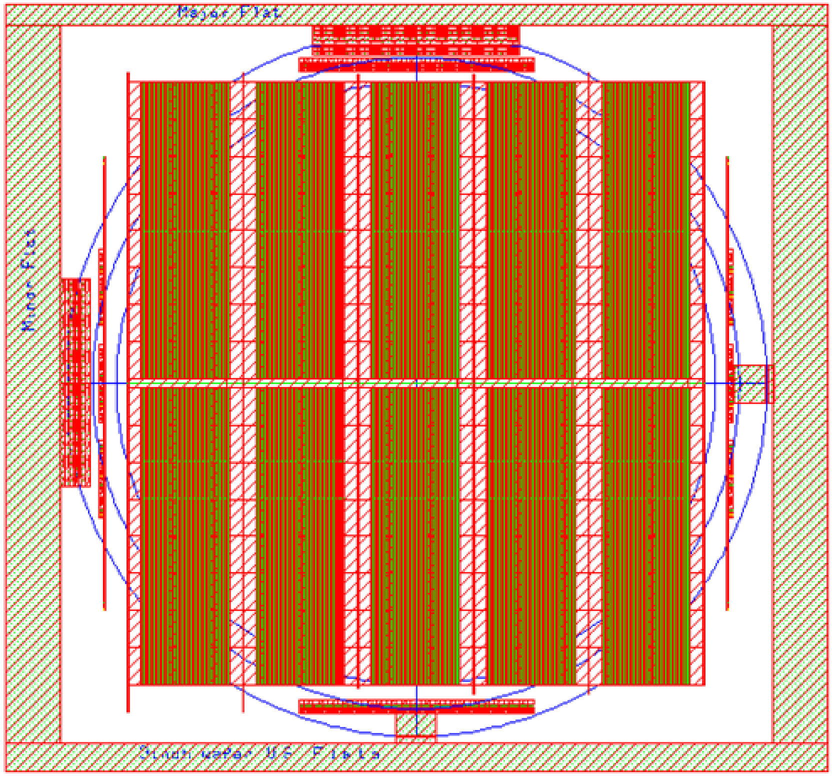


Figure 4.1 Photomask for LD cells. Outer blue circle represents the 3” diameter wafer. Rectangles are 12mm wide cells containing multiple 4mm cavity length LD-bars.

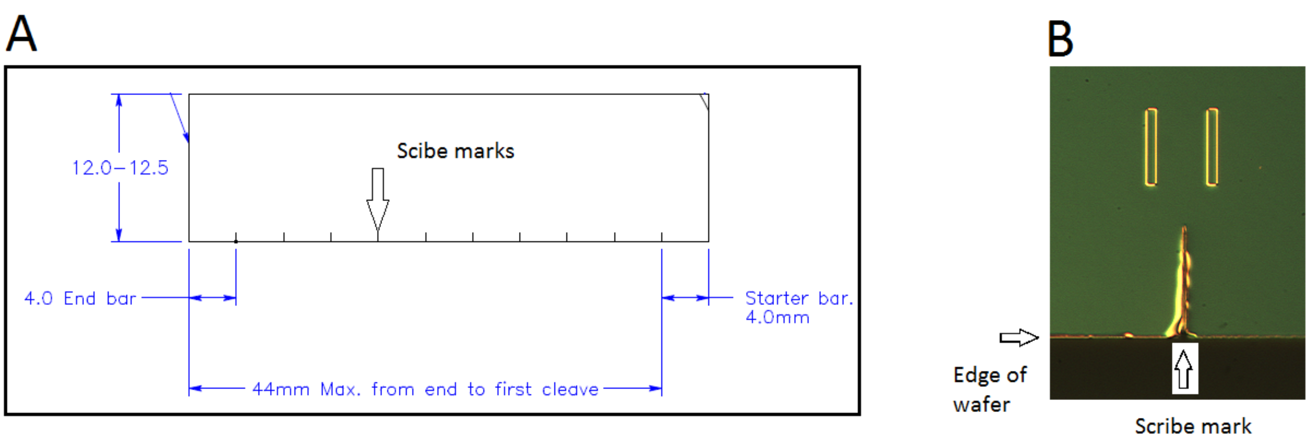


Figure 4.2A 12mm-wide LD-cell containing multiple 4mm cavity length LD-bars defined by the scribe marks.

1.2B. Photo of scribe mark.

2. Determine optical power at which LD-bar, with standard high reflectivity/low reflectivity optical coatings (OCs), fails by catastrophic optical damage (COD).

Status: Complete

- LD-bars with nineteen, 100µm-wide emitters on 500µm pitch were fabricated by CEO using their standard but proprietary LD-bar fabrication procedure.
- Diodes were attached to EPIC heatsinks using SRL's proprietary indium diffusion bond and tested.
- Typical light-current-efficiency curves are shown in Fig. 4.3. The threshold current (~10A) and slope efficiency (~1.15W/A) are typical of commercial 4mm cavity length LDs. P_{COD} of the first failure is ~170W (~9W/emitter), also typical of commercial 4mm cavity length LDs.

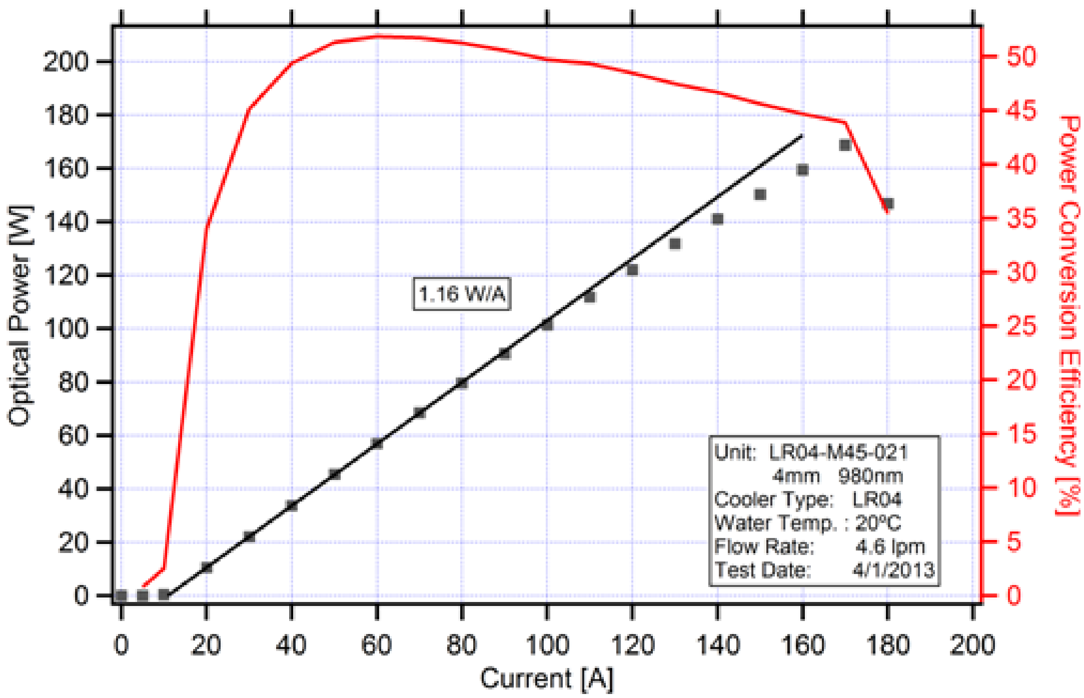


Figure 4.3 Typical Light-current-efficiency data for LD-bar with nineteen, 100µm-wide emitters on 500µm pitch.

3. Demonstrate that ohmic contacts are unaffected by exposure to intended MBE growth conditions, i.e. 500°C, 1hr, ultra-high vacuum (~10^{-9} Torr) [UHV].
   Status: Complete

   Three 4mm cavity length, LD-bars with nineteen, 100µm-wide emitters on 500µm pitch, purchased from Coherent (www.coherent.com) were exposed to 500°C, 1hr, UHV conditions by SVT (www.svta.com) and attached to EPIC heatsinks using indium diffusion die attach. The results were compared to devices from the same batch that were not exposed to the high temperature conditions. Typical L-I curves of both sets of devices are shown in Fig. 4.4. The high temperature conditions do not appear to affect the LD-bar performance.

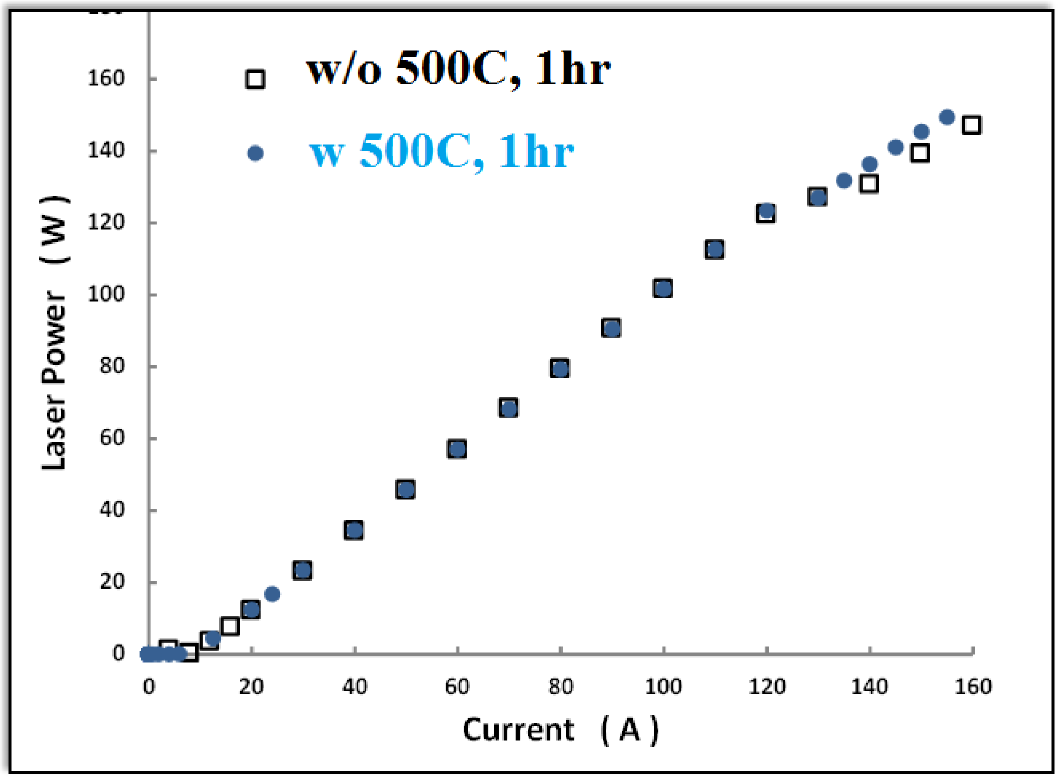


Figure 4.4 Typical L-I curve of 4mm cavity length laser diode with and without exposure to 500°C, 1hr, UHV.

4. Demonstrate cleaving of cells in UHV.
   Status: Complete

   Sample LD-cells fabricated at CEO (www.ngc.com) were cleaved in UHV by SVT (www.svta.com). No issues were found.

5. Determine MBE growth conditions at 500°C for defect free $Al_xGa_{(1-x)}As$ (x~0.2) [epitaxial passivation layer (EPL)] on <100> oriented GaAs substrates. Demonstrate EPL.
   Status: Complete

   The growth conditions for MBE growth at 500°C of $Al_xGa_{(1-x)}As$ on (100) GaAs substrate were determined by SVT (www.svta.com).

   Figure 4.5A shows a double-crystal X-ray diffraction spectrum of the final sample with an ~500nm $Al_xGa_{(1-x)}As$ layer. The separation of the $Al_xGa_{(1-x)}As$ and GaAs peaks (ΔL) determines that x~0.23. The Pendellosung fringes indicate high epitaxial material quality. The spacing of the fringes determines the layer thickness.

Figure 4.5B is a TEM cross-section of the sample in Fig. 5.1A. The TEM results confirm that the $Al_xGa_{(1-x)}As$ layer is high quality (low defect density) and the interface between the epitaxial layer and the substrate is also of high quality.

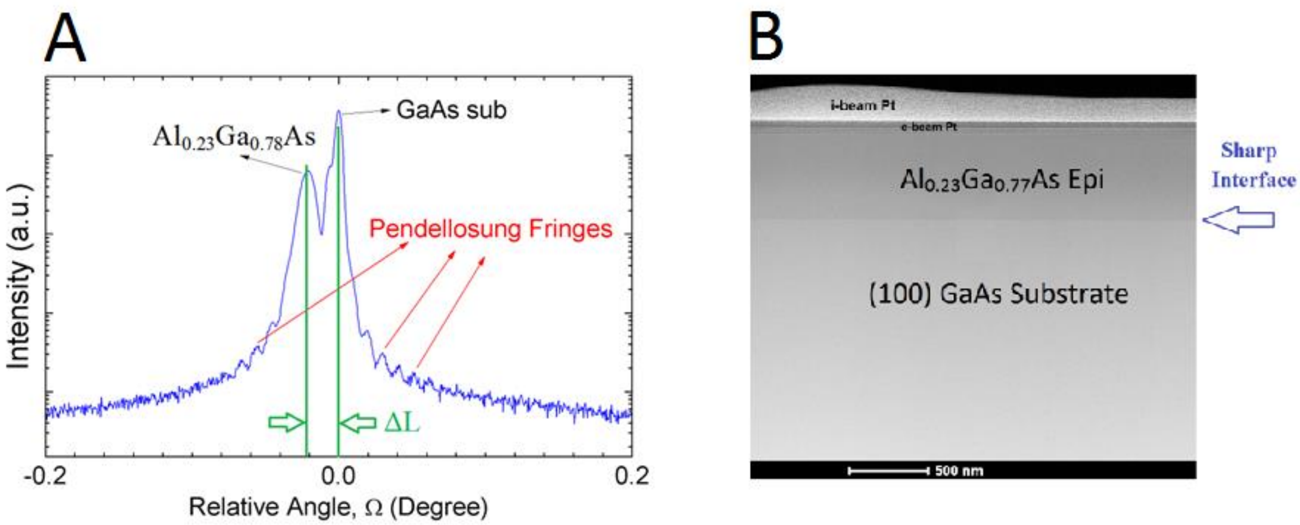


Figure 4.5 A) Double-crystal X-ray diffraction pattern of $Al_xGa_{(1-x)}As$ layer grown on (100) GaAs substrate at 500°C. B) Cross-sectional transmission electron microscopy (TEM) image of the sample in A.

6. Determine MBE growth conditions at 500°C for EPL on <110> oriented GaAs substrates. Demonstrate EPL.
   Status: Complete

   Three-inch diameter GaAs wafers oriented along the <110> direction were procured from AXT (www.axt.com) and shipped to SVT (www.svta.com) to determine the MBE growth conditions at 500°C on this substrate orientation. These substrates were required since it is difficult to determine proper growth conditions on the (110) cleaved edges of <100> oriented substrates. MBE growth uses in-situ, reflection high-energy electron-diffraction (RHEED) as crystal quality feedback during growth to optimize the growth conditions. Three inch substrates are generally ~500µm thick. A cleaved <100> oriented substrate to obtain a <110> surface results in a sample that is ~500µm wide, too small for RHEED analysis.

   Figure 4.6 shows a double-crystal X-ray diffraction spectrum (XRD) of the final sample with an ~170nm $Al_xGa_{(1-x)}As$ layer. The separation of the $Al_xGa_{(1-x)}As$ and GaAs peaks

(ΔL) determines that x~0.15. The Pendellosung fringes indicate high epitaxial material quality. The spacing of the fringes determines the layer thickness.

Figure 4.7 is a TEM cross-section of the sample in Fig. 4.6. The TEM results confirm that the $Al_xGa_{(1-x)}As$ layer is high quality (low defect density) and the interface between the epitaxial layer and the substrate is also of high quality. However, energy dispersive analysis of X-rays (EDAX) indicates almost no aluminum in the epitaxial layer. The XRD composition result is believed to be in error due to stress in the epitaxial film.

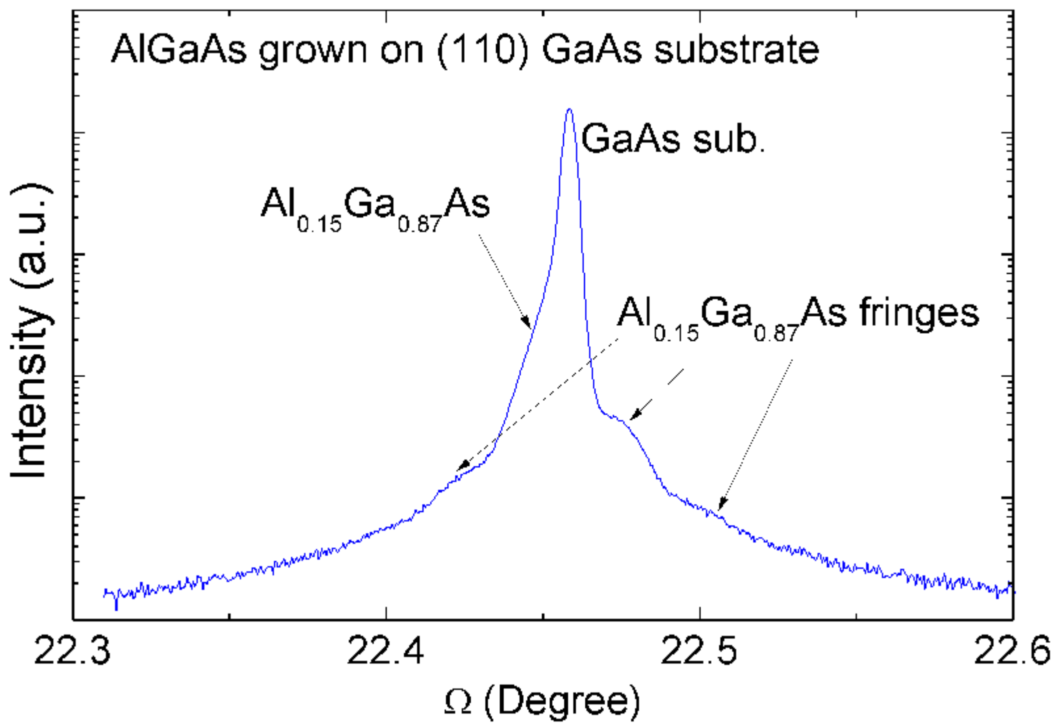


Figure 4.6 Double-crystal X-ray diffraction pattern of $Al_xGa_{(1-x)}As$ layer grown on (110) GaAs substrate at 500°C.

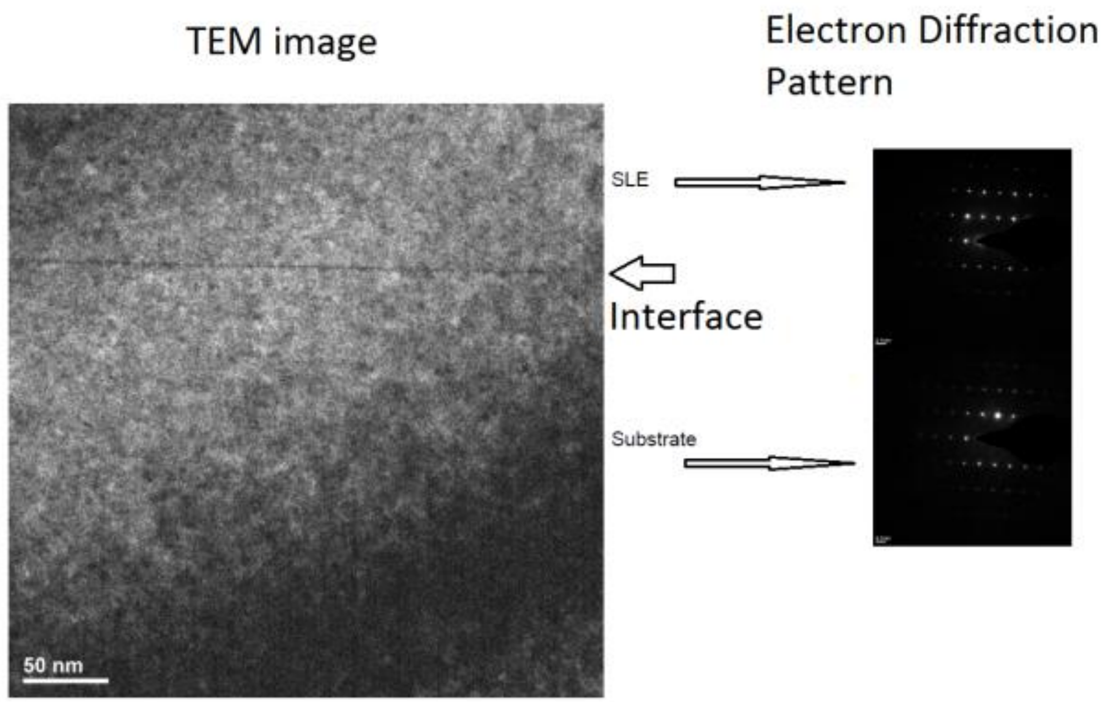


Figure 4.7 TEM image of epitaxial layer of $Al_xGa_{(1-x)}As$ layer grown on (110) GaAs substrate at 500°C. Right portion shows the electron diffraction pattern.

7. Determine MBE growth conditions at 500°C for EPL on single (110) facet, formed in air, of LD-bar. Demonstrate EPL.
   Status: Complete

   LD-bar cells fabricated at CEO (www.ngc.co) were cleaved into individual 4mm LD-bars and stacked in a fixture designed by SVT (www.svta.com). An $Al_xGa_{(1-x)}As$ epitaxial layer was grown on one facet by MBE at 500°C. No surface defects were observed on the epitaxial layer using Nomarski microscopy at 500X. Figure 4.8 shows a TEM cross-section of the LD-bar at the InGaAs quantum well. The epitaxial layer is ~237nm thick. The epitaxial layer and the interface between the passivation epitaxial layers with the epitaxial layers of the LD are defect free. The only issue is that the EDAX of the passivation layer shows less than 1 atomic per cent of aluminum.

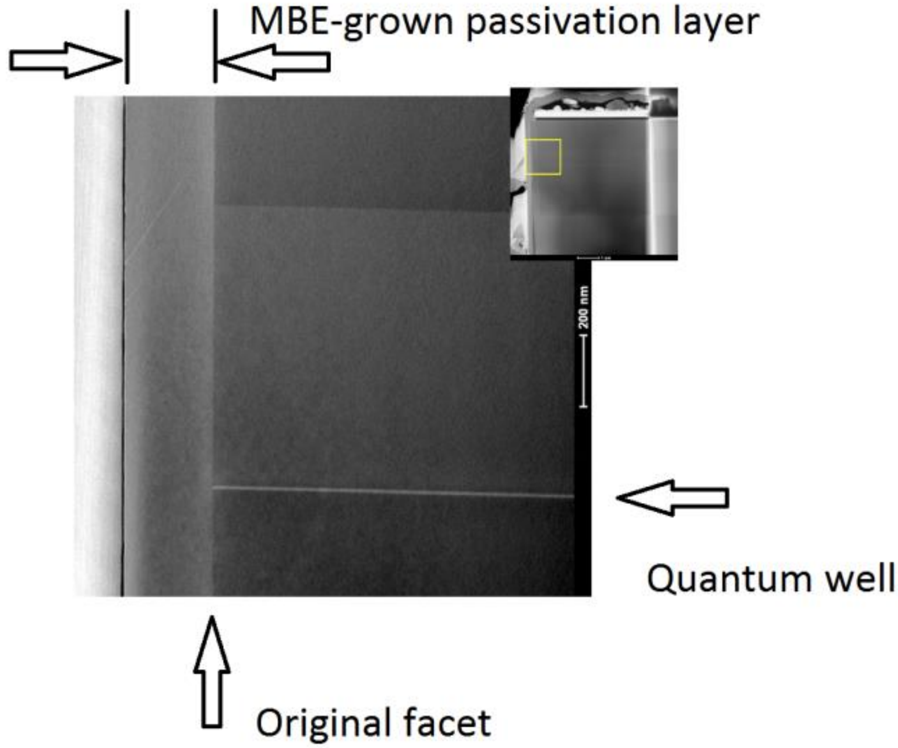


Figure 4.8 TEM image of $Al_xGa_{(1-x)}As$ (~237nm thick) layer grown by MBE at 500°C on the facet of a processed 980 LD-bar.

8. Determine MBE growth conditions at 500°C for EPL on both (110) facets, formed in UHV, of LD-bar. Demonstrate EPL and apply standard OCs.
Status: EPL Complete

LD-bar cells fabricated at CEO (www.ngc.co) were cleaved into individual 4mm LD-bars and stacked in a fixture designed by SVT (www.svta.com). An $GaAs/Al_xGa_{(1-x)}As$ epitaxial layer was grown on one facet by MBE at 500°C. The fixture was then flipped in the ultra-high vacuum chamber and an $GaAs/Al_xGa_{(1-x)}As$ epitaxial layer was grown on the other facet by MBE at 500C.

Figure 4.9 shows a TEM cross-section of the front facet of the LD-bar at the InGaAs quantum well at two magnifications. The passivation consists of an initial 24Å thick GaAs epitaxial layer to prevent the initiation of stacking fault defects. The subsequent 200Å thick AlGaAs epitaxial layer was also free of material defects.

Figure 4.10 shows a high magnification TEM cross section of A) the front facet and B) the rear facet. The rear facet passivation consists of 20Å of GaAs followed by 240Å of AlGaAs. The passivation layers on the rear facet are also defect free.

To the best of our knowledge, this is the first time that GaAs/AlGaAs epitaxial layers have been successfully grown on the (110) facets of a laser diode structure.

The bars have been sent to Cutting Edge Optronics to deposit a low reflectivity front facet optical coating and a high reflectivity rear facet optical coating. The final activity will be to attach the coated laser diode bars onto heatsinks for testing.

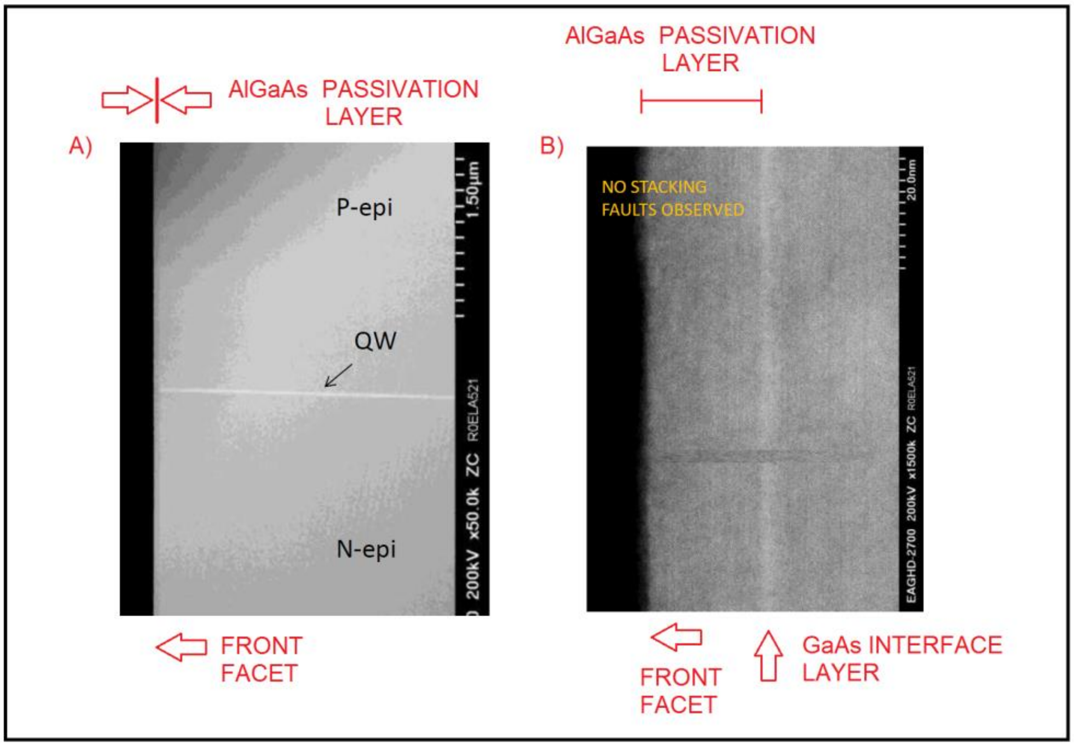


Figure 4.9 A) Low magnification cross section of laser diode front facet showing the quantum well (QW) and the epitaxial passivation layer grown by MBE.

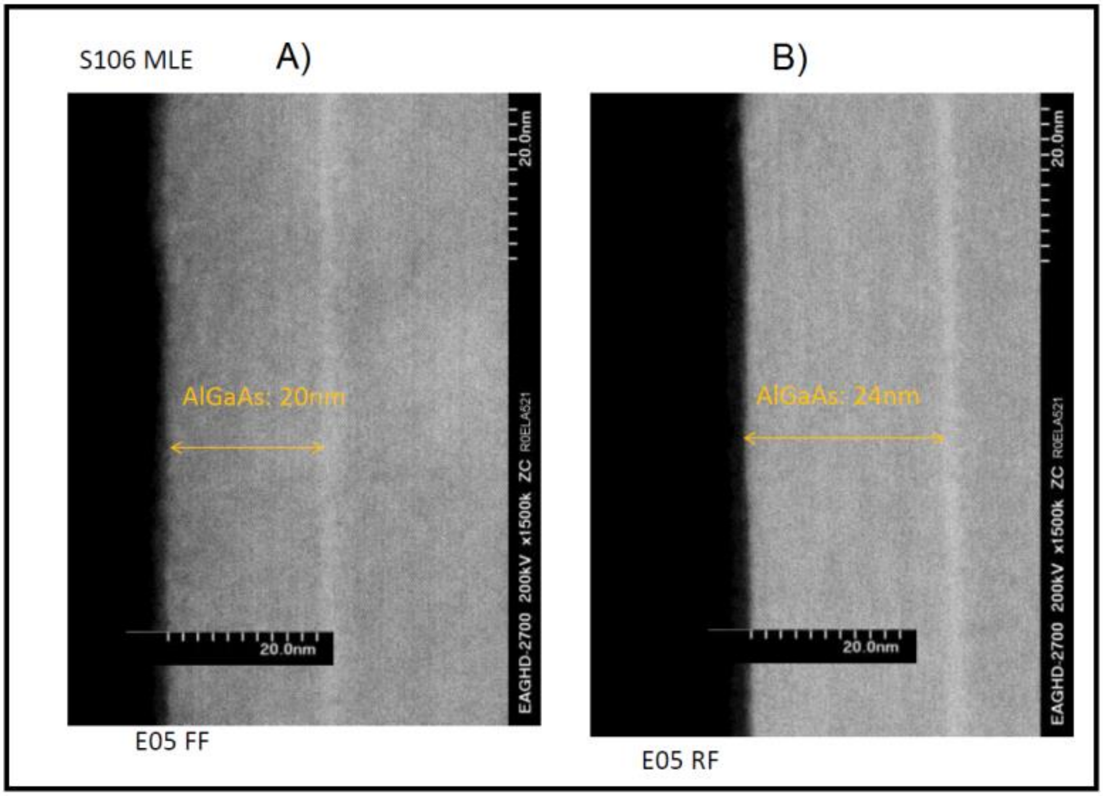


Figure 4.10 Cross section of laser diode A) front facet and B) rear facet showing the epitaxial passivation GaAs/AlGaAs layers grown by MBE.

9. Determine optical power at which LD-bar, with EPLs and OCs, fails by catastrophic optical damage (COD).

Status: EPL Complete

In this final portion of the study, we use two laser diode wafers that were fabricated into cells of laser diode bars as discussed in section 4 above. The cells were separated into four groups. All wafer fabrication and thin-film facet coating were performed by Cutting Edge Optronics (CEO) to minimize variations.

1. Group 1: Cells cleaved into laser diode bars in air and the facets coated with electron-beam deposited high reflectivity (HR) and anti-reflection (AR) thin-film coatings that are standard in the laser diode industry. Group 1 is the comparison group.
2. Group 2: Cells cleaved into laser diode bars in ultra-high vacuum and stacked. Each facet was coated with ~100Å of an electron-beam deposited amorphous silicon thin-film by SVT Associates. After breaking vacuum, the passivated bars were shipped to CEO for HR and AR coating deposition. This process is essentially the E2 passivation procedure developed by IBM and is considered to be one of the best facet passivation procedures.

3. Group 3: Cells were cleaved into laser diode bars in ultra-high vacuum and stacked. A thin, single-crystal, undoped, GaAs passivation-layer were grown on each facet, as described in Section 8 above. After breaking vacuum, the passivated bars were shipped to CEO for HR and AR coating deposition.
4. Group 4: Cells were cleaved into laser diode bars in ultra-high vacuum and stacked. A thin, single-crystal, undoped, $Al_xGa_{(1-x)}As$ passivation-layer were grown on each facet, as described in Section 8 above. After breaking vacuum, the passivated bars were shipped to CEO for HR and AR coating deposition.

Approximately 10 bars from each of the four groups were attached onto EPIC micro-channel heatsinks using an indium diffusion die attach. The reproducibility of both the heatsink and die-attach procedure have been established at SRL over a period of ~5years and several hundred devices. The packaged laser diode bars were driven to failure by COD.

Table 9.1 lists the power, from low to high values, at which each of the laser diode bars in each group failed by COD. Only two devices in Group 4 were functional most likely due excessive defects in one or both epitaxial AlGaAs passivation layers and the data should be ignored.

Figure 9.1 plots the data in Table 9.1 for comparison. The ordinate is the power at COD and the abscissa is the cumulative probability. The abscissa scale is such that a normal distribution appears as a straight line. Figure 9.2 compares Group 1 with Group 2. Figure 9.3 compares Group 1 with Group 3.

Catastrophic optical damage (COD) of a laser diode is ultimately caused by absorption of optical power at the front facet. The growth of an epitaxial layer on the facets is intended to eliminate the optical absorption of the laser light at the original facet and produce a new semiconductor surface whose absorption at the lasing wavelength is significantly less than that of the original facet.

Analysis of Fig. 9.1-9.3 indicates the following.

The distribution of the powers at which laser diode bars fail by COD are similar for Group 1-3. The main difference is in the high power tails of the distributions beyond the first standard deviation (~84%). Group 1 is limited to ~180W as expected for an unpassivated facet. Group 2 and Group 3 do not appear to be limited indicating reduced absorption at the front facet. Group 3 shows the highest values for COD power.

It is difficult to obtain a more definitive conclusion based on data from 19-emitter laser diode bars. The COD power for such a bar is the lowest value for the 19-emitters.

Table 9.1 List of power at which a laser diode bar fails by COD for each of four groups.

Group 1	Group 2	Group 3	Group 4
(No passivation)	(E2 passivation)	(GaAs passivation)	(AlGaAs passivation)
(W)	(W)	(W)	(W)
80	70	70	30
80	80	110	140
100	120	110	
110	140	120	
130	150	130	
160	160	130	
170	160	160	
180	180	210	
180	190	220	

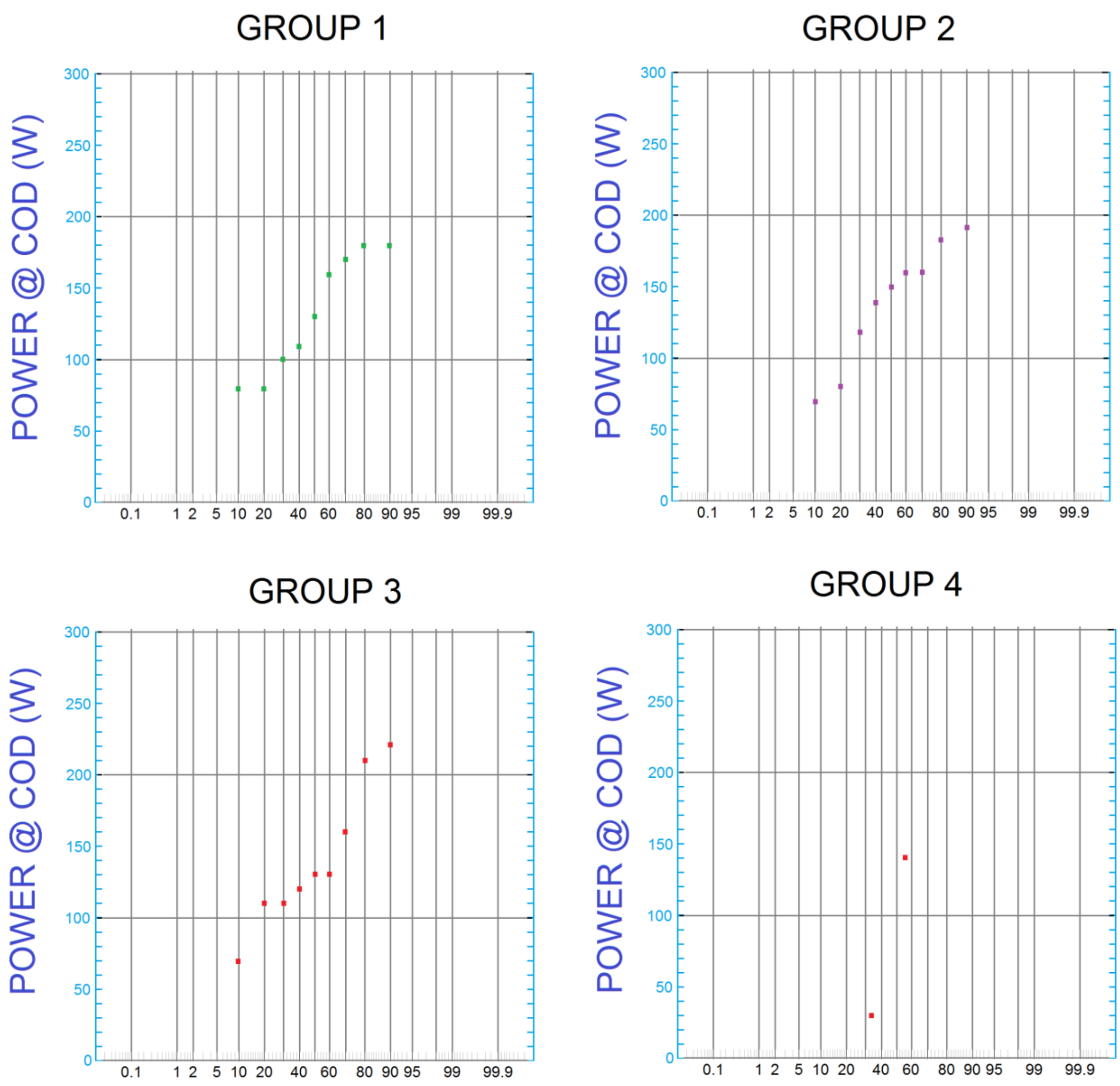


Figure 9.1 Power @ COD vs cumulative probability

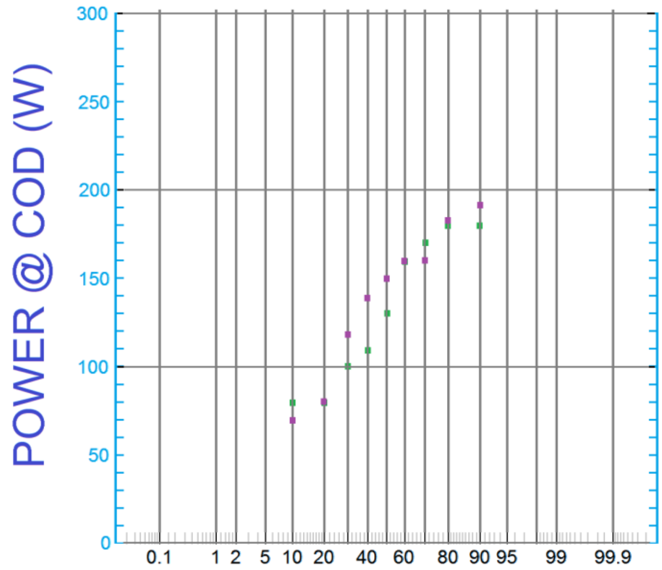


Figure 9.2 Comparison between Group 1 (green squares) and Group 2 (purple squares).

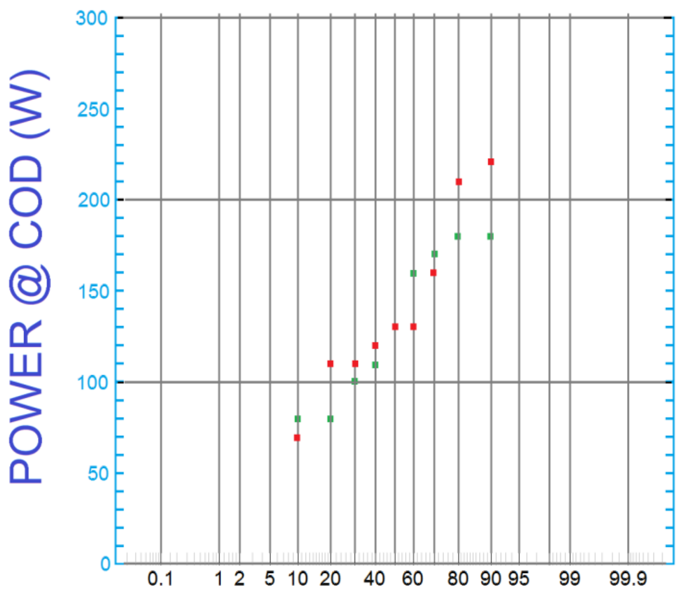


Figure 9.3 Comparison between Group 1 (green squares) and Group 3 (red squares).

Program Achievements

Standard procedures to grow defect-free epitaxial-layers of GaAs and $Al_xGa_{(1-x)}As$ epitaxial layers by molecular beam epitaxy (MBE) involve:

- growth of GaAs/AlGaAs epitaxial layers on the (100) surface of a GaAs substrate
- a large substrate surface to allow heating the GaAs substrate to a uniform temperature as well as accurately measuring the substrate temperature for process feedback and control.
- heating the GaAs substrate to a temperature in the range of 600°C-700°C to increase the surface mobility of the components of the molecular beam thus increasing the crystal quality of the epitaxial layer; increasing substrate temperature also improves the crystal quality of the epitaxial quality by desorbing atomic and molecular contaminants)

In this program, there are a number of achievements:

- Epitaxial growth of defect-free, GaAs/AlGaAs on the (110) surface of a GaAs substrate at 500°C using MBE.
- Epitaxial growth of GaAs/AlGaAs on the (110) surface on both facets of a fully fabricated laser diode bar at 500°C using MBE. The facets were 12mm by ~100μm, causing difficulties in establishing the proper substrate temperature for high quality growth conditions.
- Demonstration of increased COD power of 9xx laser diode bars using a single crystal epitaxial passivation layer.